Longitudinal-mode control in integrated semiconductor laser phased arrays by phase velocity matching

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The spectrum of semiconductor laser arrays with separate contacts is investigated. It is demonstrated that the individual laser currents can be selected such that the array operates in a single longitudinal mode in contrast to the multimode nature of its individual constituents. Moreover, it is possible to tune the lasing frequency by varying the laser currents. Wavelength tuning range of ~ 50 Å, with tuning rate of ~ 5 Å/mA, is demonstrated. It is suggested that these spectral features, characteristic of lasers which are coupled in parallel, result from the strong frequency dependence of their spatial mode pattern near the phase-matching frequency of their coupled waveguides.

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Reports on the performance of semiconductor laser phased arrays were concerned, thus far, mainly with the high-power and the small beam-divergence features of these devices.[1–5] A major characteristic of phased arrays, however, is their spectral mode structure. Evidently, this characteristic is inherently related to the degree of phase coherence among the different elements of the array, which in turn affects the far-field pattern. Spectra of both gain-guided and index-guided laser phased arrays were found to exhibit, generally, multilongitudinal-mode operation.[2,5,6–8] In all these devices, however, the individual array elements were electrically connected in parallel, by a common contact. In this letter we describe the spectral features of the recently developed separate-contact laser array.[9] With this type of array, it is possible to bias each laser independently of the others, which introduces a new degree of freedom in the operation of such devices. We show that the spectrum of an array, operating in the phase-locked mode, can be significantly different from that of any of the individual lasers of which it is comprised. In particular, we demonstrate that it is possible to choose the laser currents such that operation of the array in a single longitudinal mode is obtained, even though each laser within the array exhibits multimode operation, when it is operated by itself. Furthermore, by varying the different laser currents, we can control not only the spectral width of the array, but also its lasing frequency, thus leading to a novel type of tunable laser source. A simple theoretical model is proposed in order to explain these spectral features.

Figure 1 shows a schematic cross section of the separate-contact array. The individual laser stripes, $\sim 4\,\mu$m wide each and on 9-μm centers, were delineated by using proton implantation. Separate contacting was accomplished by employing two-level metalization.[9] The lasers were operated under low duty cycle pulsed conditions, and the threshold current $I_{\rm th}$ of each individual laser was typically 60 mA.

The spectrally resolved near field of the laser array was obtained by imaging its output facet on the entrance slit of a spectrometer, using a $20\times$ objective lens. The output of the spectrometer was displayed on a monitor using a silicon-vidicon TV camera. In Fig. 2 we show the spectrum of a four-element array obtained under two different operating conditions. Figure 2(a) shows the individual spectra of the four lasers, when each of them is operated by itself, at about $1.1I_{\rm th}$. Each laser exhibited multimode operation, which is characteristic of such gain-guided lasers, with the spectrum envelope centered at about 8700 Å. When all four lasers were operated simultaneously, two major differences in the array spectrum were observed. First, the array lased at wavelengths which were longer by 50–100 Å, compared with the wavelengths in the individual spectra [i.e., those shown in Fig. 2(a)]. This behavior was observed in all the arrays that were tested. Second, the position of the lasing wavelengths as well as the spectral width were a function of the lasers current combination. In particular, it was possible to select the laser currents such that single longitudinal-mode operation was obtained. In Fig. 2(b) we show an example of such a case. This spectrally resolved near field was obtained when the four lasers were operated with $I_1 = I_4 = 40$ mA and $I_2 = I_3 = 30$ mA [I_i indicates the current of the ith laser from top, in Fig. 2(a)]. Note that the wavelength of the collective mode of the array is ~ 80 Å longer than the center of the individual laser spectra. The observed tuning range of such arrays was 50–100 Å.

In order to further investigate the origins of this spectral behavior, we examined the spectrum of two lasers, a and b separated by 18 μm, while the laser c between them was

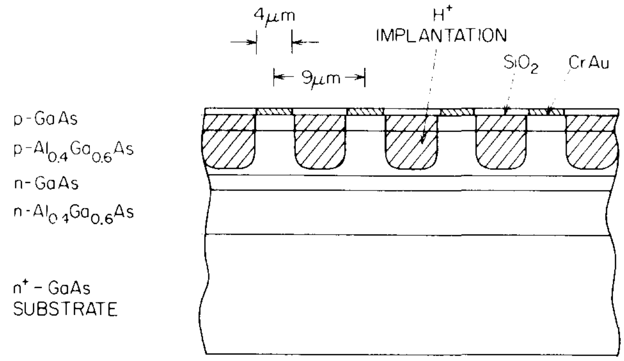

FIG. 1. Schematic cross section of the semiconductor laser array.

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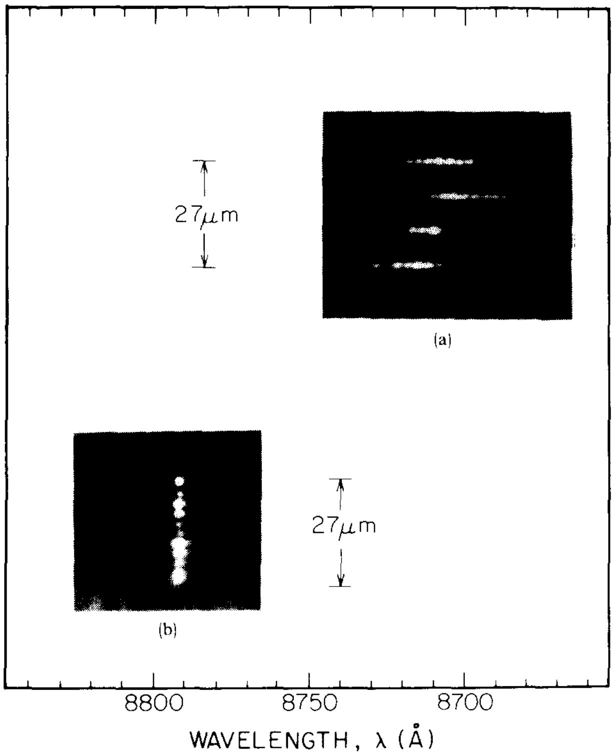

FIG. 2. Spectrally resolved near fields of a four-element laser array. (a) Individual spectra, obtained when each laser is operated at $\sim 1.1 I_{th}$ by itself. (b) Collective spectrum, obtained when all lasers are operated simultaneously, with $I_1 = I_4 = 40$ mA, $I_2 = I_3 = 30$ mA (I_i is the current of ith laser from top).

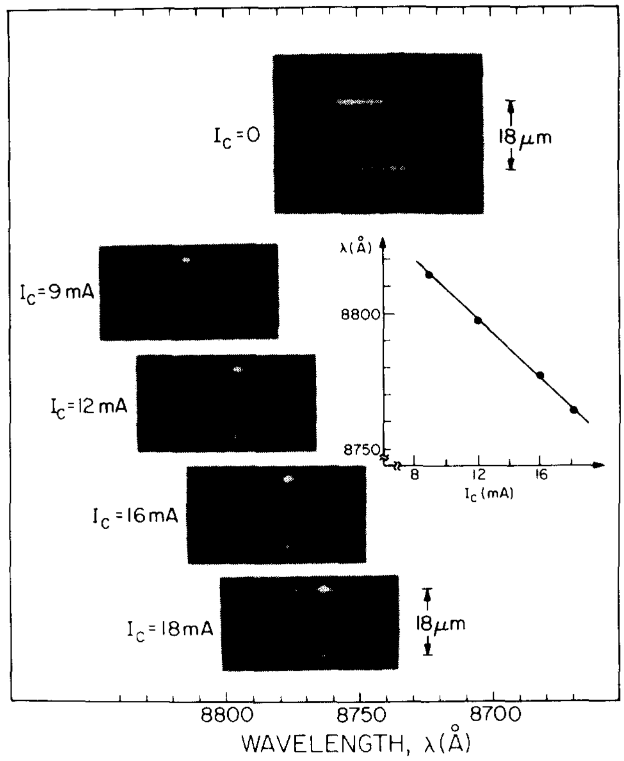

FIG. 3. Spectrally resolved near fields of an array of two lasers, separated by 18 μm, for various values of the current I_c through the stripe between them. The insert shows the wavelength λ of the main longitudinal mode for different currents I_c.

biased below threshold. This simulates a two-element laser array in which the gain between the two lasing filaments can be controlled.[10] In the presence of gain between their stripes, lasing of the coupled lasers occurred in a quasi-single mode, at wavelengths up to ~100 Å longer than the centers of their individual spectra. By increasing the current I_c through the center laser stripe, the lasing mode wavelength could be tuned towards shorter wavelengths. An example of such tuning is shown in Fig. 3. In this case, the tuning range was ~50 Å and the tuning rate was ~5 Å/mA. As the current through the center stripe was further increased, the lasing wavelength hopped to longer wavelengths once again, which was followed by tuning toward shorter wavelengths, as before. This time, however, the spatial mode pattern was different. At still higher currents, spatial modes with larger intensity below the center stripe appeared, and the tuning became less orderly.

In order to explain the spectral features of the phased arrays, the following model is suggested. Consider first the case of two lasers coupled in parallel. The spatial modes supported by such a structure can be constructed (in the case of weak coupling) by coupling the modes of the otherwise isolated laser waveguides, to form the "supermodes" of the combined structure. The spatial patterns of these supermodes depend weakly on the mode frequency, except in the vicinity of the frequency ω_0 at which the propagation constants of the otherwise isolated modes, β_1 and β_2, are equal, i.e., the separate waveguide modes are phase matched. In this phase-velocity matching domain, the supermode power is divided more or less equally between the two waveguides. Outside the phase-velocity matching domain, the intensity of the supermodes is restricted to either one of these channels. This dependence of the supermode intensity pattern on frequency, which is illustrated schematically in Fig. 4(a) is predicted by the coupled-mode formalism.[11] It is this behavior of the supermode pattern which is responsible for the wavelength selectivity exhibited by lasers that are coupled in parallel. Due to the lower loss in the region between the coupled lasers, the modal gain of the supermodes is larger for frequencies within the phase-matching domain since at these frequencies the intensity distribution can best take advantage of the interchannel gain so that the supermode gain exceeds that of the individual channel gain. In particular, for a given coupling coefficient κ between the coupled modes,[12] one can choose the laser cavity length L such that only one of the supermode Fabry–Perot (FP) resonant frequencies will fall within the phase-matching domain. A sufficient condition for such single-mode operation is

$$\kappa L \lesssim \pi(\Delta n_{\rm eff}/\bar{n}_{\rm eff}), \qquad (1)$$

where $\Delta n_{\rm eff}$ is the difference between the slopes of the dispersion curves of the coupled waveguides and $\bar{n}_{\rm eff}$ is the average effective group index. Furthermore, the domain of phase-velocity matching can be tuned to different wavelengths by changing the refractive index of either region in the coupled waveguides (e.g., by variation of the laser currents). The index variation results in change in the dispersion curves of each coupled waveguide which, in turn, causes the phase-

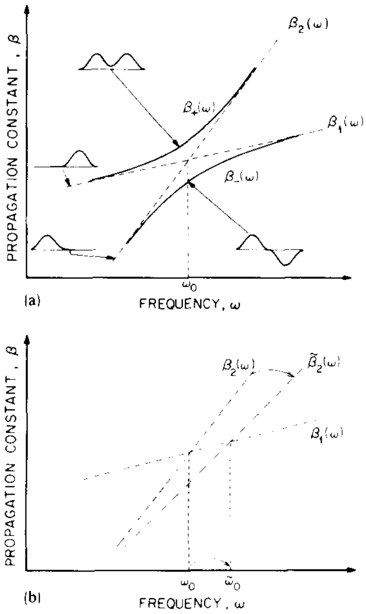

FIG. 4. (a) Dispersion curves of two individual modes (β_1 and β_2) and two coupled modes (β_+ and β_-) in two coupled waveguides. The inserts show schematically the corresponding field patterns. (b) Illustrating the tuning of the phase-matching frequency, caused by the change in the dispersion curve.

matching frequency ω_0 to shift, as shown in Fig. 4(b). This tuning of ω_0 would result, of course, in tuning of the laser frequency. The above considerations can be applied to laser arrays with more than two channels as well, leading to essentially the same picture.

The model described above qualitatively explains the wavelength selectivity and tuning features that were observed in the spectra of our phased arrays. The single-mode operation of the four-element array (as shown in Fig. 2) occurred when phase matching between all modes of the individual channels was achieved at a FP mode. The wavelength tuning described by Fig. 3 resulted from the change in the refractive index, mainly in the region between the two laser filaments, brought about by the variation in the carrier concentration. The observed operation of the coupled modes of the array at longer wavelengths may arise from the lower loss in the region between the stripes at longer wavelengths and/or the larger coupling coefficient at larger wavelengths. A similar shift in the wavelength of two coupled, gain-guided lasers was observed by other workers as well.[13,14]

The phase-velocity matching model described above should apply as well to laser structures with multiple active regions, reported recently.[15,16] In particular, it should account for the wavelength selectivity observed in the double active layer lasers of Tsang *et al.*,[15] although in contrast with the present work, these workers interpreted this selectivity as arising from coincidence in the resonant frequencies of the FP modes of the different parallel cavities,[17] and not phase-velocity matching.

In conclusion, we demonstrated control of the longitudinal modes in phased arrays with separate contacts. Both reduction in the number of lasing modes (to ~1) and wavelength tuning were obtained by varying the laser currents. The spectral features of such devices, in which the lasers are coupled in parallel, were interpreted as arising from the phase-velocity matching among the coupled waveguides which occurs in a limited range of frequencies. Tunable and single-mode lasers based on this principle may have advantage over other types of lasers with longitudinal-mode control because of their relatively simple fabrication procedure, and the inherent possibility of obtaining higher power outputs and smaller beam divergence.

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